Research-informed design, management and maintenance of infrastructure slopes: development of a multi-scalar approach

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Research-informed design, management and maintenance of infrastructure slopes: development of a multi-scalar approach

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Abstract. The UK's transport infrastructure is one of the most heavily used in the world. The performance of these networks is critically dependent on the performance of cutting and embankment slopes which make up £20B of the £60B asset value of major highway infrastructure alone. The rail network in particular is also one of the oldest in the world: many of these slopes are suffering high incidents of instability (increasing with time). This paper describes the development of a fundamental understanding of earthwork material and system behaviour, through the systematic integration of research across a range of spatial and temporal scales. Spatially these range from microscopic studies of soil fabric, through elemental materials behaviour to whole slope modelling and monitoring and scaling up to transport networks. Temporally, historical and current weather event sequences are being used to understand and model soil deterioration processes, and climate change scenarios to examine their potential effects on slope performance in futures up to and including the 2080s. The outputs of this research are being mapped onto the different spatial and temporal scales of infrastructure slope asset management to inform the design of new slopes through to changing the way in which investment is made into aging assets. The aim ultimately is to help create a more reliable, cost effective, safer and more resilient transport system.

1. Introduction and background to the research

The UK's transport infrastructure is one of the most heavily used in the world. The UK rail network takes 50% more daily traffic than the French network; the M25 between junctions 15 and 14 carries 165,000 vehicles per day; London Underground is Europe's largest at 402 km. The performance of these networks is critically dependent on the performance of cutting and embankment slopes which make up £20B of the estimated £60B asset value of major highway infrastructure alone. However, many of these assets are old; London Underground is the world's oldest underground system and much of the rail network was constructed more than a century ago. Many of these slopes are now suffering from excess deformation and high incidents of instability (which is showing evidence of increasing with time). These problems cause delays and subsequent economic loss to UK industry, and the general public, and pose a safety hazard. The risk of derailment from slope failures is the greatest risk faced by the railway infrastructure. Between August 2003 and December 2009, a total of 429 incidents of failure of Network Rail (NR) earthworks were recorded across the rail network, causing 66 days in delays. It is not only safety but economics that is important: emergency repairs cost 10 times that of planned works. Therefore the impact of reducing delays caused by slope failure will be highly significant in both direct economic and indirect social and economic terms.

At the same time, the UK is poised to start investing billions of pounds in new transport infrastructure, with the proposed high speed line between London and Birmingham (HS2) representing the most high profile of cases. The construction of earthworks for high-speed rail causes additional challenges as they will suffer increased dynamic loading from the higher loads imposed by the trains. Furthermore, inspection and maintenance, currently an integral part of the management of earthworks assets, will need to be undertaken with little or no human access and this will demand new remote techniques. Design of such structures will therefore need to ensure long-term stability whilst also minimizing land-take as the route that the line will take passes through highly valuable estate.

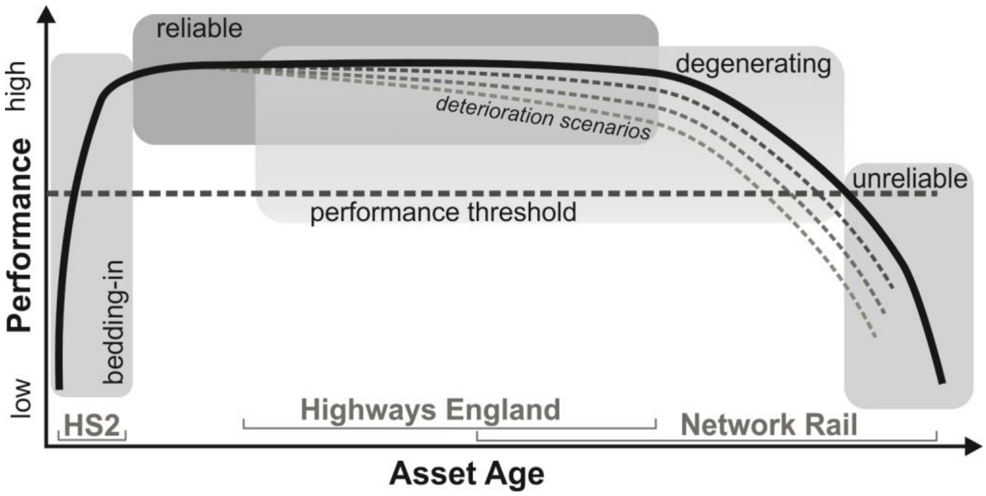

Figure 1. Generalised deterioration model for transport earthworks (adapted from Thurlby, 2013).

Figure 1 illustrates the performance of the asset in relation to its age and summarises the challenge for owners and operators of transport earthworks. This challenge is slightly different for each of the asset owners: Network Rail needs to be able to reliably identify which assets are most unreliable or deteriorating the fastest in order to target resources most effectively at repair; Highways England needs to allocate resources at repair but also to understand how smaller interventions can slow down deterioration and maintain reliability for longer; HS2 need to understand how to design for longer life and to recognise the signs of deterioration through remote monitoring/inspection. However, they all have in common the need to better understand the mechanisms and rate of deterioration, and whether this is likely to increase in the future. They also need to understand possible triggering events which precede catastrophic failure and the most effective mitigation and adaptation/remediation strategies and techniques. Additionally, they all need to make cases for investment, either to justify the design for a new build, as in the case of HS2, or for more pro-active maintenance and repair to improve resilience.

The research described in this paper was developed in collaboration with asset owners and their consultants to ensure that there is a synergistic relationship between the underpinning science of the research and the knowledge required to better design, manage and maintain a safe and resilient transport network. To this end our research has been structured around 3 physical scales, as illustrated in Figure 2.

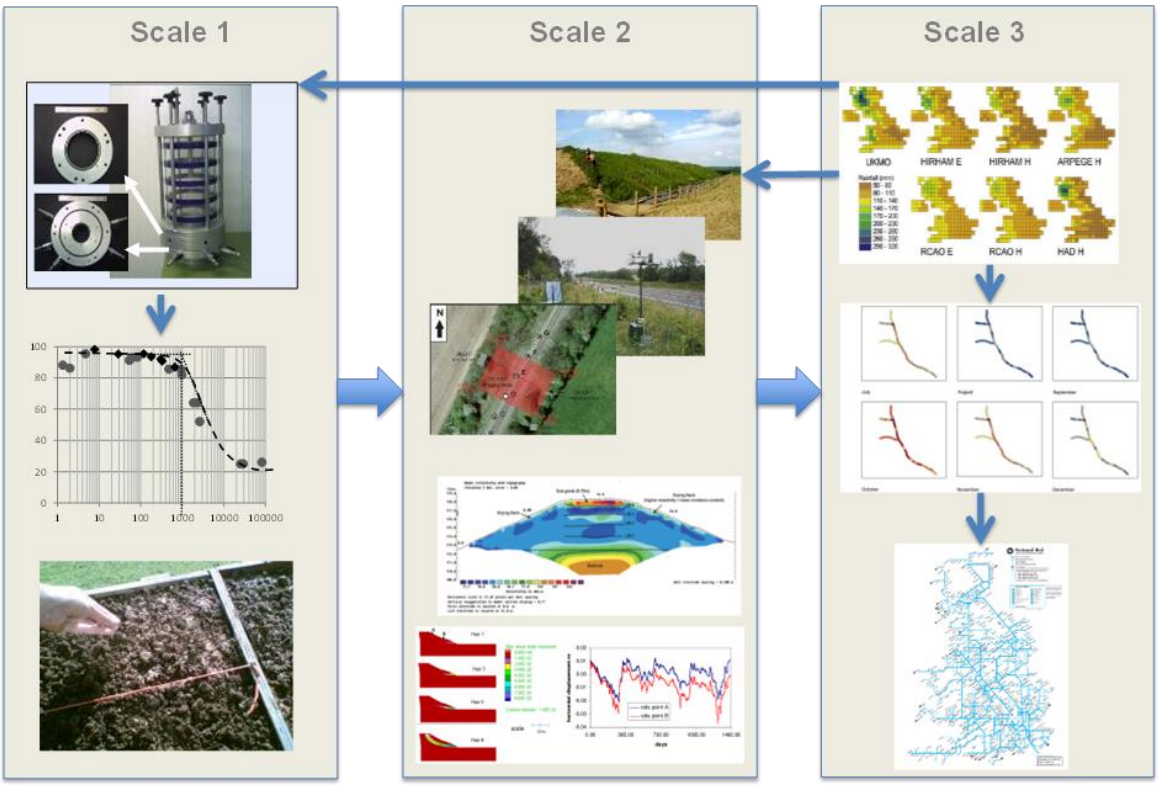

Figure 2. Research structure and integration across scales.

The aims are to understand materials (particularly clay fills) and the soil-water-vegetation system behaviour (scale 1), and how this affects the behaviour of single slopes (scale 2) that make up a transport network (scale 3). We also aim to understand these systems under current and future, generated weather event sequences and to be able to integrate the understanding across these 3 scales. These three scales map effectively onto the knowledge required by asset owners in that: Scale 1 enables advice to be provided on material properties that can be used in design; Scale 2 maps onto operational asset management at the level of a single asset and the design of monitoring and remediation measures; Scale 3 feeds firstly into Tactical Asset Management at the level of groups of assets to set regional performance targets, and then into Strategic Asset Management at the scale of a whole portfolio of assets, across a whole business, to enable setting of targets to achieve strategic goals and to inform investment priorities.

This paper sets out the progress made to date in the research on the iSMART (infrastructure Slopes: Sustainable Management And Resilience Assessment), which is 2 years in to a 3.5 year programme. The paper is structured around the scales illustrated in Figure 2 and will aim to comment on the integration between these scales and the messages we have been able to provide to the project stakeholders.

2. Weather Impacts

It is now widely accepted that climate change is occurring and that this will affect the processes and parameters that determine the stability of slopes. There remains, however, significant uncertainty in forecasting these changes in the medium and long-term. The UK has experienced a sequence of extreme weather events in recent years that have resulted in large increases in the number of both constructed and natural slope failures. Winter storms in December 2013 to February 2014 resulted in above average rainfall that brought widespread impacts and damage to the UK including landslides and flooding. This followed the record rainfall in April to July 2012 breaking previous records, and

November 2012 a sequence of heavy rainfall events resulted in one of the wettest weeks in England in the last 50 years (www.metoffice.gov.uk/climate/uk/interesting/november-2012). As a direct result, four times the number of landslides was recorded in Great Britain in the months of July, November and December 2012, above monthly averages for previous years (Pennington et al. 2014, 2015). On the UK rail network failure rates increased from the average of 50 per year to 150 slope failures in 2012 and 170 failures in 2013 (Brown, 2014). While these periods of extreme weather cannot be directly attributed to climate change, the resulting impacts demonstrate the importance of understanding slope failure processes linked to weather, and they provide examples of events that are forecast to occur more frequently in a changing climate.

Dijkstra and Dixon (2010) discuss the critical design cases for the stability of slopes. In the short term, slope systems can be regarded to be in a steady state with a relatively stable set of processes and parameters determining slope stability. Presently, most design and management of slopes is carried out on the basis of this assumption, sometimes enhanced by using a contingency if the site is particularly sensitive and long-term stability is questionable. These relatively crude assessments provide results that, through experience, can be translated into appropriate designs, and operation and management strategies. This may be acceptable for some design cases, however, for earthwork slopes that affect infrastructure operation, the design life of these assets is some 60 to 120 years and thus covers a period over which climate conditions are forecast to change significantly. Traditional slope models have a very limited capability to incorporate climate information (often only through applying higher water pressures or an additional factor of safety) and are therefore not suited to address long term assessments of slope stability variations in any detail. It is plausible that during the design life of a slope the magnitude of change in climate controls (mainly expressed in terms of changes in precipitation, temperature and sea level rise) will be such that the processes controlling stability will change significantly. Recurrence intervals between key critical events may shorten, recovery times of slopes may not be fully available and the system may enter a stage of severe instability (Dijkstra and Dixon 2010). Changes in antecedent pore pressures and alteration of trigger event magnitudes will lead to a change in the frequency, distribution and mode of earthwork slope failures, as a consequence of combined changes in the triggers (e.g. precipitation events) and conditioning or preparatory factors (e.g. the antecedent groundwater conditions).

The UK Climate Projections 2009 (UKCP09) are the current best available information on forecast climate change in the UK. The projections show that in the 2080s, and under a medium emissions scenario: all areas of the UK warm on average relative to the 1961-90 baseline; summers warm more than winters, particularly in southern England; mean daily maximum and minimum temperatures increase across the UK in both summer and winter; and average annual precipitation changes little across the UK, but winter precipitation increases in western regions while summer precipitation decreases in many, but not all, parts of the UK (Murphy et al. 2009). UKCP09 addresses the uncertainties of earlier projections by producing probabilistic outputs using a multi-model ensemble; running one model over and over with different parameterisations, and including runs from other models (e.g. Collins, 2007). It uses three pre-determined emissions scenarios (Low, Medium and High Emissions) and the resultant probabilistic projections are targeted 30-year "decades" from 2020s to 2080s (the ‘baseline’ is maintained as the period from 1961-1990). Projections are available at 25km resolution for the whole of UK, averaged over each month, seasonally and annually (Jenkins et al. 2009; Murphy et al. 2009).

To provide further detail, a weather generator has been produced that builds on the EARWIG weather generator developed at the Universities of Newcastle and East Anglia (e.g. Kilsby et al. 2007; Jones et al. 2009). Typical daily precipitation values for 1961-1990 are used as input and users are able to turn these into statistically equivalent daily values for some time in the future, using transformation functions in the form of rainfall characteristics and UKCP09 monthly climate change projections (Wilks and Wilby 1999). This is relevant to a resolution of 5km. In addition, it is also possible to analyse the output by applying user-defined daily weather thresholds. Access to UKCP09 information is through a web interface that allows users to create customised image products. These probabilistic forecasts of future climate form a promising development in the quality of the climate data for input into slope stability models (Jenkins et al. 2009; Murphy et al. 2009; see also www.ukcip.org.uk for further up-to-date information). However, the challenge for slope stability modelling communities is to develop their capabilities further to reach a status where the full potential on offer from the climate modellers can be used effectively in the broad assessment (i.e. not sporadic and site specific) of long-term slope stability development (Dijkstra and Dixon 2010).

At present there is insufficient knowledge available to be able to model slope failure processes on a probabilistic basis. Therefore, following the approach developed by Dijkstra et al. (2014) a number of weather event sequences are extracted from the ensemble outputs of the weather generator using the high-emissions scenario outputs from UKCP09 centred on the 2050s. This ensemble output comprises 100 runs of a 30-year period (i.e. 3000 sets of annual weather event sequences), which provides a set of weather years that can be used to interrogate modelled slope performance. The weather event sequences are a primary input into the coupled hydrological- vegetation-soil behaviour modelling (described in Section 5). As a first step to develop and assess the modelling approach we have used the historical weather data for one of our field sites at Newbury, UK. The extended period of detailed monitoring has enabled the data to be categorised statistically in terms of return period and it is fortuitous that the data contain both extremely hot and dry, and extremely wet summer seasons. The approach is summarised in Section 3.

Now that the modelling approach has been validated against field data, a systematic parametric study will be undertaken. In this case, all combinations of annual precipitation and annual temperature for 3000 weather event sequences were plotted, determining for the resultant point cloud the shape of the convex hull, and taking a sample of 16 sequences from this convex hull. These sequences thus represent combinations of average annual precipitation (very wet to very dry) and temperature (very hot to very cold), providing suitable input series to evaluate model responses.

3. Field monitoring and experimentation

3.1 Field sites

Because of the extremely long expected life-times over which earthworks assets exist, a deep understanding of their behaviour can only be gained through long-term monitoring programmes. Long-term data sets from a number of exemplar embankment and cutting sites are being used to calibrate whole-slope numerical models (which are described in Section 5). Data are being collected from a number of sites set up by the project partners prior to the start of the iSMART project. The sites are illustrated in Figure 3 and summarised as follows:

- Newbury, Berkshire: an 8 m high highway cut slope in London Clay, built 1999, with rough grass and shrub cover (Smethurst et al, 2012).
- BIONICS, Newcastle: a purpose built embankment research facility, comprising a 6 m high, 90 m long Glacial Till embankment built in 2006 with extensive in-ground instrumentation and climate control over parts of the slope (Hughes et al, 2009; Glendinning et al, 2014).
- Loughbrickland, Northern Ireland: A 10 year old, 24 m high road cutting in Glacial Till overlying fractured, permeable shale, built and instrumented in 2003 to measure pore water pressure/suction and near surface water content changes (Carse et al, 2009).
- Laverton, Gloucestershire: a railway embankment about 6 m high constructed around 1900 via end tipping of local Charmouth Mudstone.
- Craigmore, Northern Ireland: a 22 m high, 150 year old steep railway cutting in Glacial Till overlying low permeability granite bedrock.
- Hawkwell, Southend: an 8 m high London Clay embankment, built c1880. Mature trees on the slope were felled in March 2007 to give the present rough grass and shrub cover.

Figure 3. Monitored Field sites.

The first four of these have been the focus of field experiments and modelling during the project so far. The sites have a wide geographical distribution within the UK, and are intended to reflect a range of slope and material types, are of differing age and construction quality, and have different vegetation covers. The intention is that they reflect the broad range of slopes typical of UK highway and rail systems.

The following measurements are being made at sites:

- Climate: sites have locally installed weather stations to measure rainfall, and the parameters required to calculate potential evapotranspiration (temperature, relative humidity, wind speed and solar radiation). Climate stations have also been installed to investigate the variations with slope aspect. Cut-off trenches have been installed to measure runoff and interflow through the topsoil, which allows a full water balance to be estimated based on rainfall, evapotranspiration and interflow/runoff.
- Pore-water pressures and suctions are being measured using flushable piezometers, and tensiometers closer to the surface. High suction tensiometers and other devices are being used to measure suctions over 80 kPa, which occur in the clay soils close to the ground surface in a dry summer.
- Soil water content is being measured using a neutron probe, point measurement devices that measure resistivity or permittivity of the soil, and electrical resistivity tomography (ERT) which uses surface arrays to obtain two or three-dimensional distributions of moisture in the ground.
- Lateral displacements are being measured using standard inclinometers and a ShapeAccel Array (SAA; a continuously datalogged in-place device), and vertical displacements using magnet extensometers.

Not all sites contain all of the instruments described above, however under the iSMART project a small number of additional devices have been installed to allow clearer comparisons between sites. Where possible measurements have been recorded at short time intervals using data loggers.

3.2 Utilisation of long-term data sets.

Many of the sites have now been monitored for several years, which has allowed changes in soil water content, pore water pressures/suctions, and displacements to be linked to particular sequences of weather received over the duration of the monitoring period. Smethurst et al (2012) use simple water balance models to show how soil water content and pore water pressures can be linked to the climate. They then use a long-term rainfall record of 42 years to show that over a six-year period of monitoring at the Newbury site it received both fairly dry and wet extremes (for example, 2007 had the wettest summer in the record, while 2003 was a 1 in 10 year dry summer). As clay slopes react to longer periods of climate, this can be used to define the range of soil water content and pore water pressures that result from these more extreme periods of weather. This process is illustrated in Figure 4, and includes profiles of pore water pressure/suction associated with particular return periods for climatic events, based on the data measured at Newbury.

This careful characterisation of the climate in conjunction with long-term monitoring of pore water pressures and displacements has ensured that:

- The worst case (or near worst case) wet winter pore water pressures are captured;
- Cycles of pore water pressures at depth, likely to drive both shallow and deeper-seated progressive failure mechanisms in slopes, are characterised;

The iSMART project is continuing work to monitor and characterise the behaviour of the exemplar sites and to build long-term data-sets for use by the research community. Additionally, the BIONICS site is being used to study the effects of imposed ‘designed’ rainfall events more closely. Furthermore, the ERT array installed within the BIONICS embankment, which allows us to visualise the water regime continuously through the embankment cross section, is being used to investigate the effects of surface features, such as cracks, on the sub-surface water regime.

While data collected above can be used to ensure that the numerical models correctly characterise the changes in pore water pressures and effectives stress, and incremental increases in strain (or displacement), none of the exemplar slopes is actively failing, and thus there is more uncertainty about the ability of models to correctly determine failure. Wider sets of data are therefore also being provided by the project stakeholder partners, through access to their databases, to provide evidence of the number of, mode, and likely trigger event for failures in clay slopes across the railway and highway networks. These will be used to benchmark the results of the numerical parametric study (Section 5).

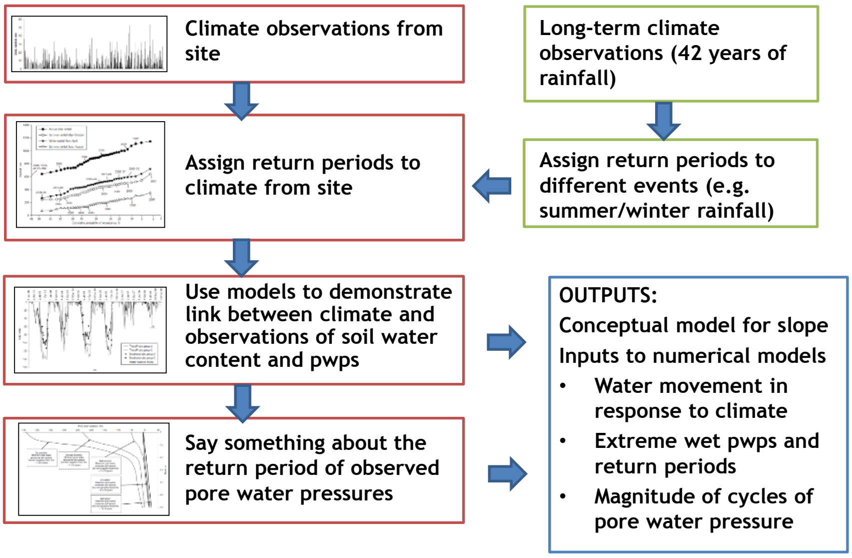

Figure 4. Use of long-term weather observations to inform slope modelling.

4. Materials testing

The central aim of the laboratory testing work is to both provide parameters required for the numerical modelling and to gain a deeper understanding of the effects of weather event sequences on the deterioration of soil properties. Of particular interest is to understand soil water retention behaviour for engineered slopes, soil volume change under suction cycles for our fill materials and changes to the mechanical properties of engineered fills due to the effects of desiccation, vegetation and climate. This advanced and detailed understanding of the mechanical properties of clay fills, including the deformation and deterioration mechanisms produced by cycles of pore water pressures informs numerical models as described in Section 5. Further materials testing is being conducted at field scale, particularly for the determination of permeability, where soil fabric and mass characteristics play an important role.

4.1. Laboratory testing

4.1.1 Soil water retention behaviour. Soil water retention behaviour is important to determine as it governs and explains many observations in behaviour of unsaturated soils. A Soil Water Retention Curve (SWRC) for a soil consists of water content, either gravimetric or volumetric, plotted against suction, as shown in Figure 5.

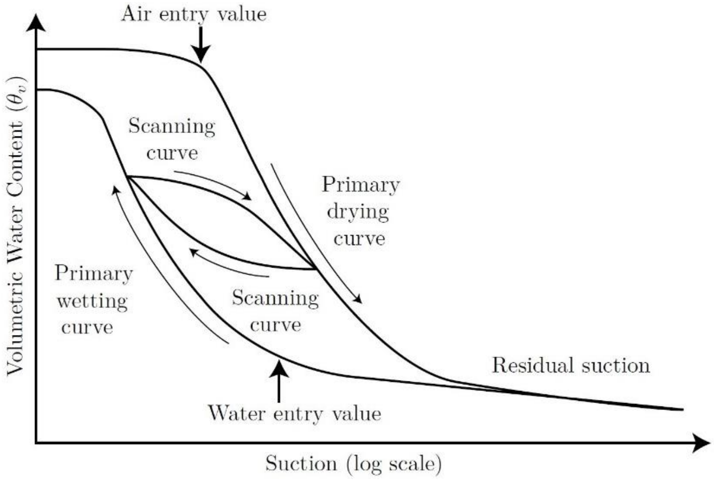

Figure 5. Hysteretic soil water retention behaviour (after Toll, 2012).

The curves consist of a primary wetting and drying path with transitions between these two states occurring via scanning curves, meaning a soil may be in nearly any state between the two primary curves. When a SWRC is determined for a soil, it can be used for estimating permeability functions more accurately and for interpreting shear strengths in unsaturated soils.

Several methods exist for determining a SWRC. Three methods have been employed in the laboratory on material from the iSMART project; these are the point pressure plate apparatus, high capacity tensiometers and the filter paper method. Laboratory results shown in Figure 6 show data recorded using the tensiometer system. As can be seen in the figure a change in behaviour can be observed as samples undergo cycles of wetting and drying, potential mechanisms for which have been investigated using optical techniques described in Section 4.1.3.

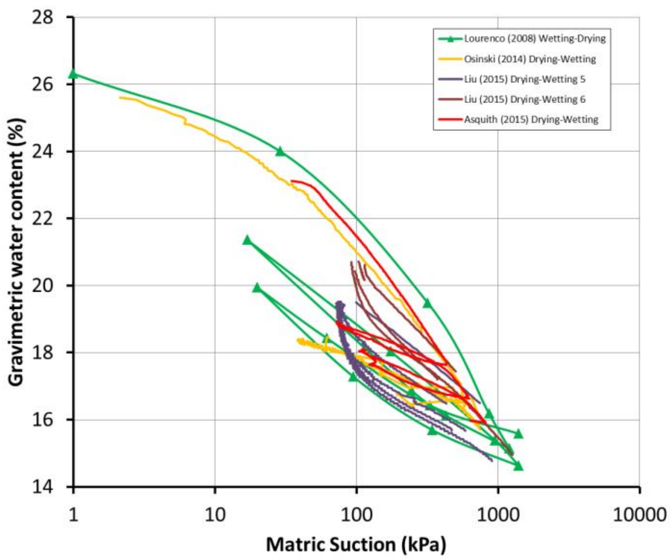

Figure 6. BIONICS soil water retention curve data using the tensiometer method.

*4.1.2 Mechanical behaviour***.** The mechanical behaviour of engineered fills will vary over life span of the earth structure that they form. These variations occur on a number of temporal scales, short term changes due to extreme wetting or drying events, seasonal changes (summer drying / winter wetting) and cumulative aging effects of exposure to many cycles of wetting and drying over decades. Mechanical testing conducted within iSMART aims to identify the mechanisms causing these changes and quantify their effects. This is being achieved through a programme of triaxial and direct tensile testing.

Triaxial Behaviour - influence of the degree of saturation on the strength of fill. Specimens were formed from material taken from the BIONICS site and compacted at differing gravimetric water contents of 15%, 20% and 22%, with nine being tested in drained saturated conditions and a further twenty seven in constant water unsaturated conditions, with suctions measured using high capacity tensiometers. The high water content samples were representative of the in-situ water content of the fill and the lower value was the optimum moisture content of the soil found from compaction testing. The unsaturated samples were tested both compacted at the original water content and also at the two other water contents after undergoing wetting or drying.

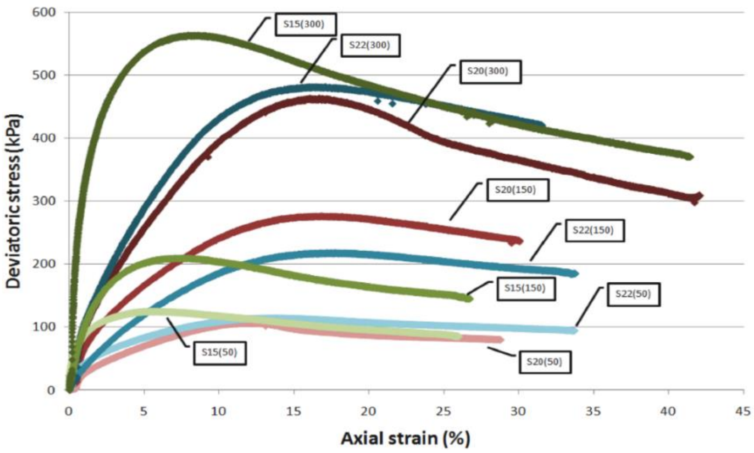

Figure 7. Stress strain plot for saturated triaxial testing of BIONICS material (after Mendes, 2011).

The results for the saturated tests are shown in Figure 7, and the unsaturated test results shown in Figure 8. The unsaturated tests showed that samples with a lower water content had increased strength due to suction, whilst increasing the water content reduced the peak strength. With all samples at 15%, clear strength peaks could be observed with a shearing plane forming in the failed samples whilst samples with a higher water content failed by bulging in a plastic ductile manner. In summary, it was observed that at lower water contents samples behaved with higher strengths, higher stiffnesses and this can be attributed directly to the higher suctions within the samples.

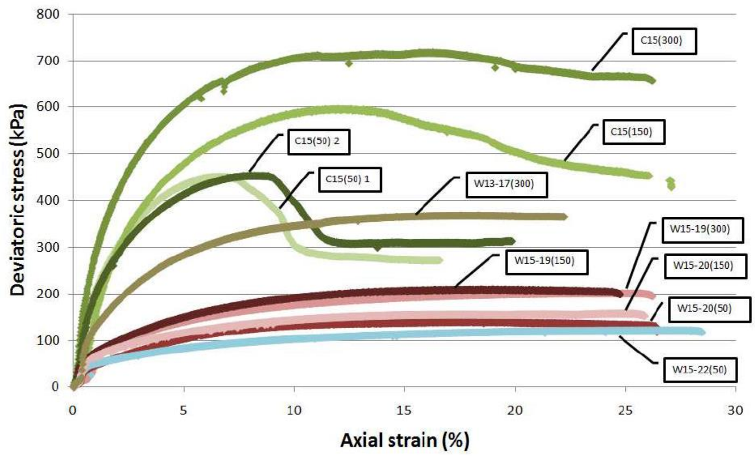

Figure 8. Stress strain plot for unsaturated testing of BIONICS material (after Mendes, 2011).

Drained stress path testing – strength reduction due to cycles of pore water pressure and viscoplastic straining (creep). A series of triaxial tests has shown that a reduction in soil strength occurs when pore water pressures are cycled at effective stresses below the peak failure stress. Cuttings in over-consolidated clay are known to be susceptible to progressive failure, with softening of the toe and the development of a rupture surface into the slope, potentially due to cycles of pore pressure cycles in response to weather events. Laboratory testing on reconstituted samples has been carried out to investigate the time-dependent behaviour of till. The research has shown that under elevated close to constant deviator stresses (70-90% peak strength), the till can accumulate a significant amount of shear strain due to pore water pressure cycling of ±5kPa (Harley et al., 2014). Furthermore, it has been shown that till may also reach its ultimate state simply by creeping when held under constant effective stresses conditions close to failure (Carse, 2014; Harley et al., 2014). Laboratory observations also indicate that the creep rate increases depending on how much a material has softened. Figure 9 shows data where pore water pressures were cycled (±5kPa) at 80% peak strength, and data where pore pressure was held constant at 80% peak strength. Note the acceleration of creep rate due to pore pressure cycling in comparison to a sample left to rest. The sample which was left to rest accumulated a significant amount of shear strain and caused a reduction of ~20kPa in peak strength of the material.

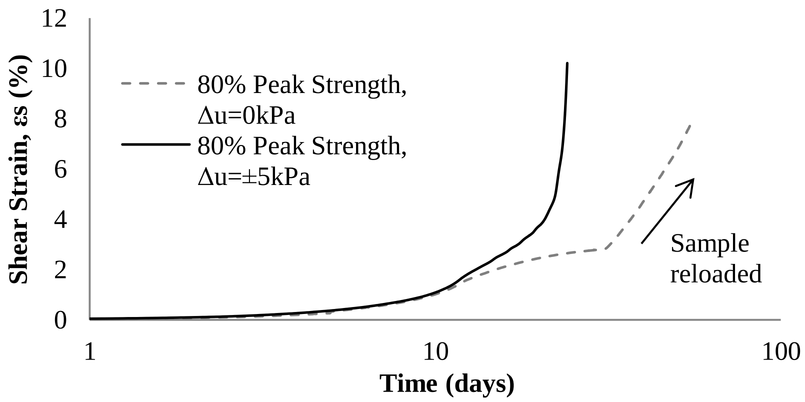

Figure 9. Development of shear strains under constant deviator loading.

Quick undrained triaxial behaviour – strength and stiffness reduction due to cycles of wetting and drying. A series of unconsolidated undrained triaxial tests have been performed on 38mm diameter, 76mm long samples of material from the BIONICS site compacted in the laboratory to densities representing field conditions (Glendinning et al, 2014; Hughes et al, 2009). A detailed description of the methodology may be found in Hen-Jones et al. (2014). The authors acknowledge that quick undrained triaxial tests will not capture the true unsaturated shear strength of the material as no suction measurements are made but the trend of strength changes does provide insight into the long term performance of the material.

Figure 10 shows the results of two cycles of wetting and drying on the compacted fill specimens. Shear strength can be seen to increase with reduction in water content and subsequently decrease with increase in water content. During the wetting phase, lower water contents are achieved than the drying phase for the same water contents and the lower strengths are exhibited for both wetting and drying phases in the second cycle when compared to the first implying a permanent change in material property.

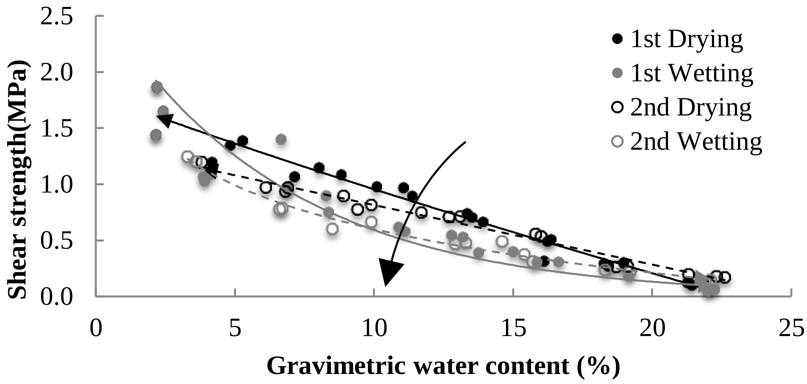

Figure 10. Relationship between undrained shear strength and gravimetric water content during cycles of wetting and drying.

Tensile behaviour. Cracking has an impact on soil mass permeability, strength and stiffness throughout the slope profile and hence slope failure susceptibility. Knowledge of the tensile strength in varyingly saturated conditions is essential to understand the initiation, propagation and ultimate extent of cracking. This has implications for the degradation of near surface material that governs the critical and changing interaction between engineered infrastructure slopes, vegetation and the atmosphere.

Recent investigations into the relationship between tensile strength and soil water content upon repeated drying and wetting cycles in material won from the BIONICS site have been conducted using a direct tensile strength test modification to standard direct shear apparatus. The mechanics and capabilities of this test method are further described by Stirling et al. (2015).

The tensile strength trend with hydraulic cycling is presented in Figure 11, after Stirling et al. (2014) and shows a similar trend of deterioration with increasing cycles of wetting and drying behaviour to the undrained shear strength data presented above.

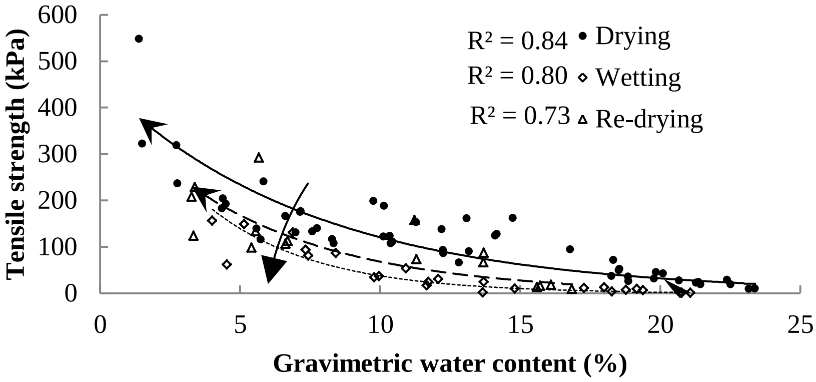

Figure 11. Tensile strength relationship upon initial drying, wetting and re-drying (after Stirling et al, 2014).

4.1.3 Fabric and Micro-structure. To investigate the potential causes of the deterioration in material properties observed in the triaxial and tensile tests, micro-structural changes were investigated on specimens post-testing using an Environmental SEM. This technique enabled the temperature and pressure of the immediate atmosphere around the specimen to be prescribed in order to control humidity and ultimately, influence drying rate. A detailed methodology will be described in Hen-Jones et al. (2015).

Figure 12 displays a clearly visible crack produced as a result of desiccation. Upon closer inspection of this feature (Figure 12b), particles lining the crack wall are found to have aligned during drying-induced shrinkage and have created a distinct coating to the crack surface. After the specimen was removed from the E-SEM and rehydrated by the application of a distilled water droplet and left to homogenise overnight, the specimen surface was again surveyed. Figure 12c exhibits a much more hydrated clay texture and is centred about a relic crack feature. This location is further magnified in Figure 12d and demonstrates both the partial closure and apparent infilling of a previously wider crack aperture. However, such a feature has remained identifiable and is likely to be a product of the permanent realignment of particles at the crack wall and infilling of loose clay particles. It is therefore anticipated that this discontinuity be exploited upon subsequent exposure to drying. The potential of these micro-cracking features to be the cause of the deterioration of clay fills is being further investigated in the laboratory, in conjunction with an investigation of their implications for the long-term mass behaviour of a clay slope through field observations.

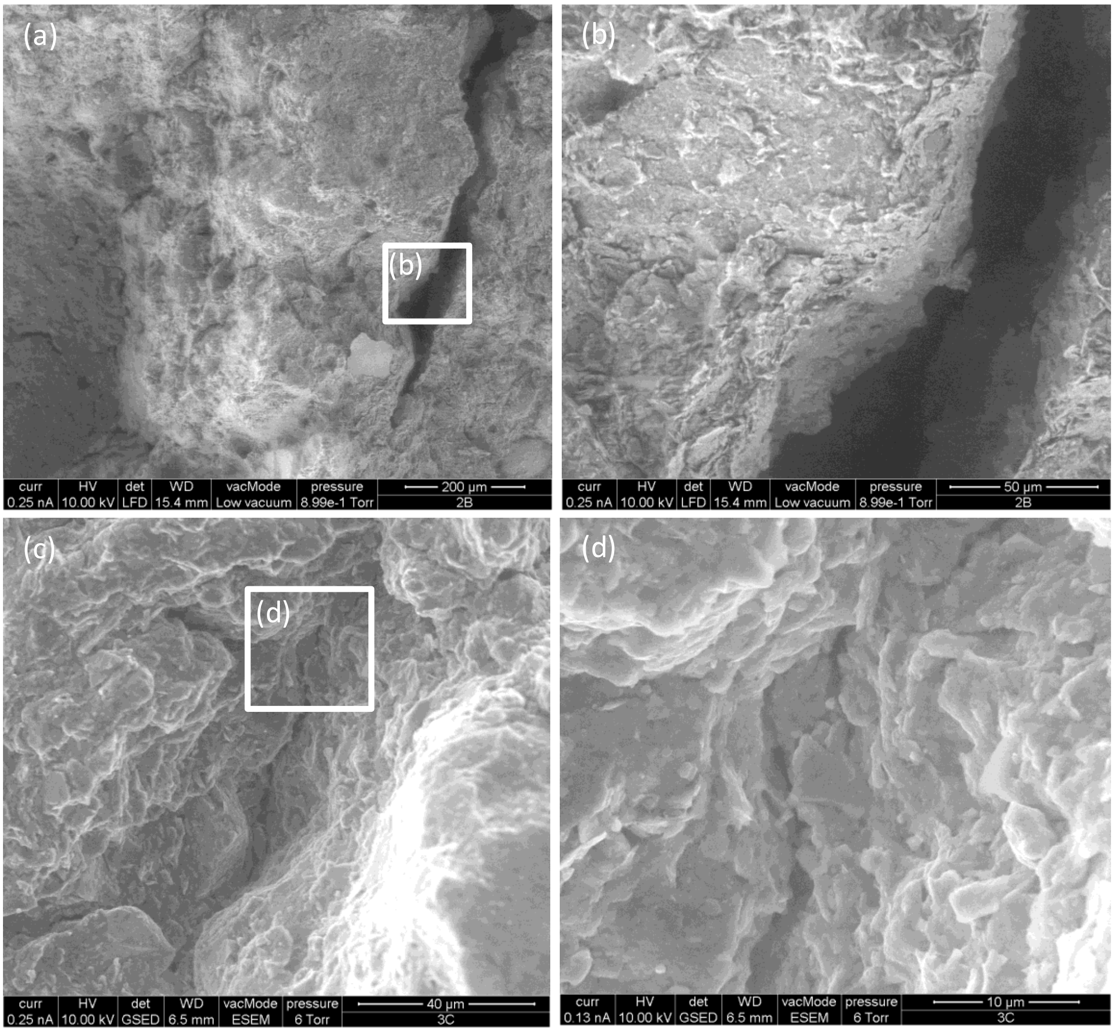

Figure 12. E-SEM images taken at two sites (a) site 1 after 90 min at 10% RH and showing the position of (b) desiccated clay particles and fracture wall under higher magnification, (c) site of reduced crack aperture following re-wetting and the position of (d) hydrated particles under higher magnification (after Hen-Jones et al. 2015).

4.2 Field testing

In addition to the laboratory testing, a series of field experiments is being used to investigate the relationship between laboratory and field-scale material behaviour. In particular, permeability is being tested in the field within the near-surface zone which is likely to have a significant influence on changes in water pressures deeper within the slope. The extent of summer clay cracking is being recorded through observations from carefully excavated trial pits, and at the BIONICS site, changes in the width of large cracks are being continuously measured using strain gauges. Surface permeability is being measured using Guelph, double ring and purposely designed infiltrometers. Initial measurements suggest that bulk permeability increases by around three orders of magnitude close to the ground surface during the summer (e.g. Glendinning et al, 2014). This increase in near-surface permeability significantly influences the ability for infiltration into the slope, and thus potentially high near- surface pore water pressures during wetter weather in autumn.

Field data is also being used to determine the SWRC in the field and to investigate the potential for change over time due to deterioration effects. Further field investigations are also being used to determine the depth of influence of wetting and drying cycles and hence the depth and rate of deterioration in the near surface zone of slopes. This understanding will then be incorporated in to numerical models, which will in turn be able to determine the long-term deterioration in stability.

5. Numerical Modelling

The numerical modelling undertaken as part of iSMART has 3 broad aims:

- To extend and validate whole slope numerical models capable of capturing critical climate-geology combinations;
- To assess the long-term behaviour of slopes and to develop an understanding of climate triggers to slope failure;
- To develop adaptation strategies and help design monitoring regimes.

In order to achieve these aims it is necessary to understand how weather sequences control the spatial and temporal pore water pressure variations in a slope and in turn understand the effect these cycles have on ultimate and serviceability limit states.

The first stage of this research has been to better understand how to model the weather-vegetation-soil-slope hydrological system. This was undertaken using a number of software codes at three differing universities. These include FLAC and SHETRAN, VADOSE/W and SEEP/W at the universities of Newcastle, Bath and Queen's Belfast respectively. Models were selected based on past experience of both researchers and stakeholders. The aim was not to develop new codes or one 'super' model, but rather to use established methods with known capabilities, in combination, to investigate the many different and varied aspects of the problem.

This exercise required a number of numerical modelling validation exercises to be run. The first of these was a simple one-dimensional drainage exercise using the problem geometry, material properties, boundary and initial conditions along with the results were taken from Forsyth et al. (1995). For reasons of brevity, this will not be reported here; the lessons learned will be included in the discussion in Section 5.2.

5.1 Modelling Newbury cutting

A hydrological modelling exercise was firstly performed as an extension of the one-dimensional caisson model, adding surface water fluxes due to weather and surface vegetation along with a two-dimensional slope geometry. The soil hydrological parameters were based on those published within Smethurst et al (2006). The meteorological parameters were derived from an on-site weather station and gaps were in-filled from nearby Met office weather station data. The modelled data produced was compared to site monitored pore water pressure data.

Coupled hydrological-mechanical modelling was undertaken using SHETRAN and FLAC Two-Phase flow only, utilising the methodology developed by Rouainia et al. (2009) in which simulated present and future climate weather time series were applied in a hydrological model of the Newbury cut-slope (using SHETRAN) to derive pore pressure variations over time. These pore pressures were in turn applied to a mechanical model in FLAC to observe the resultant deformation behaviour. A parametric study was then undertaken to investigate the influence of the soil's saturated permeability and pre-failure stiffness on slope stability.

In the modelling work undertaken to date as part of iSMART the majority of the meteorological parameters are derived from on-site weather stations or where this is not possible (or data is missing) taken from nearby Met Office weather stations. Other data (for the coupled hydrological-mechanical modelling) has been derived using a weather generator (Kilsby et al., 2007) based around the UKCIP02 data (Hulme et al., 2002). Further work is to be undertaken using future climate data derived using the updated weather generator based around the UKCP09 scenarios (Kilsby et al., 2009), as described in Section 2.

5.2 Lessons learned so far.

The caisson provided a number of useful lessons regarding the process of undertaking the modelling. In particular, modelling mesh discretisation affects the thickness of a modelled wetting zone during infiltration of water into a soil mass, which in turn has implications for the gradient of effective stress change and hence shear strength where infiltration and gravity driven flow occur within a model. This will affect the shear strength profile within a slope model with a narrower front producing a more sudden change. The initial profile of pore water pressures and degree of saturation used within a model has the capability to affect the rate of progression of a wetting front into the soil. This is a function of both the relative unsaturated permeability and additional volume of water required to saturate pore spaces. Gravitational drainage alone is not enough to generate significant suctions. To generate suctions greater than the soil's field capacity, water losses due to root water uptake and evapo-transpiration are required, which of course are an integral element of the slope modelling.

The hydrological modelling of the Newbury cutting demonstrated that it was possible to capture the broad trends with regard to the magnitude of pore pressure changes (i.e. the maximum and minimum values) and their timing in response to weather events in all three models. However the monitored data appeared to respond more rapidly to discrete events than could be captured by the modelling.

A significant outcome of the exercise was an understanding of the influence of the vegetation parameters used on the modelled pore pater pressure. The choice of vegetation parameters (where explicitly accounted for in the models) can have very significant implications for the derived rates of evapo-transpiration and the resultant surface suctions.

The leaf area index (LAI) in the VADOSE/W model (ratio of leaf area to underlying ground surface area) which in turn controls the proportion of solar energy that acts towards transpiration from the vegetation vs evaporation from the soil surface had a significant effect on the generated suctions.

An initial constant LAI value was used which allocated too much solar radiation to transpiration and in turn caused excess root water uptake and larger suction generations at greater depth than were observed in the field. A more realistic seasonally varying LAI gave a better fit to the monitored data than the original constant value by reducing energy allocated to transpiration and root water uptake for periods where vegetation canopy cover reduces. As such care must be taken when specifying vegetation parameters to account for their seasonally varying nature. Care must be taken when employing vegetation models to ensure that calibration is performed as relaying on suggested or default parameters in modelling is likely to yield poor comparison with field monitored data.

In order to derive a close match between the field pore water pressure data and those modelled using SHETRAN an increase in the permeability of the soil mass forming the cut-slope to a relatively high value of $1e^{-7}$ m/s was required (compared to a measured value of $1e^{-11}$ m/s). It was also found that the modelled evapo-transpiration from the slope was yielding significantly higher suctions than those recorded on site. This latter point was found to be due to the wind speeds used during the calibration exercise, which were in turn taken from a Met office weather station located away from the slope on open ground. The slope itself is sheltered by a stand of trees along the crest and so it was necessary to downscale the wind speed to better approximate site conditions. These two changes significantly improved the match between modelled and monitored suction generation. This exercise (along with the previous hydrological modelling study of the same slope) demonstrated the importance of model calibration against field monitored data and also the importance of site specific data.

In order to look at the potential effects of a future climate on stability, weather time series were generated for both a present and future climate based on UKCP02 climate scenarios (Hulme et al., 2002). These were used as this work extended previous studies by Rouainia et al which were carried out prior to the release of UKCP09. The weather time series were applied to the hydrological model and the resultant pore pressures then input into the mechanical model. The modelling demonstrated that for a future climate, the elevated summer temperatures led to the generation of higher surface suctions and in turn larger shrink-swell cycles causing a higher rate of material softening and progressive failure than observed for a present climate model. This can be seen in Figure 13. The sudden elevated displacements in the future climate model occurring in years three and five (as well as at ultimate failure) were caused by periods of elevated rainfall which in turn caused elevations in the peak pore water pressure at depth beyond normal values.

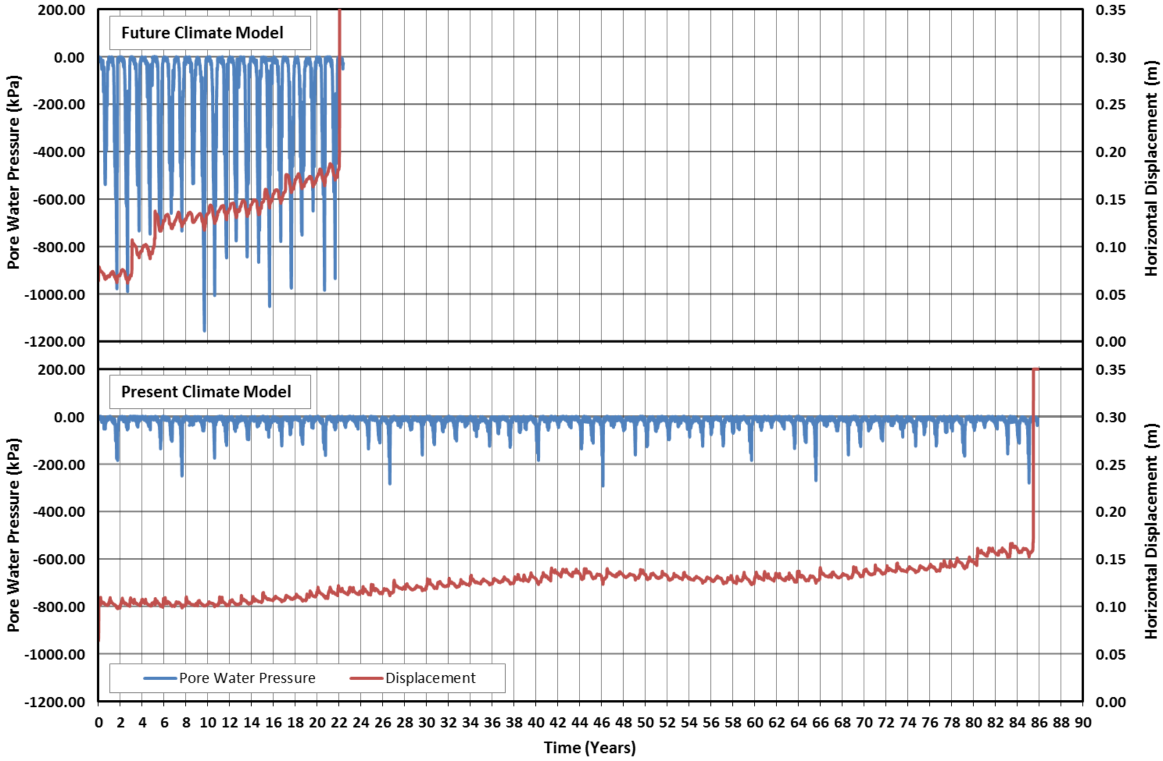

Figure 13. Mid-slope displacement and surface pore water pressure flux for a cut-slope subject to an applied present and future climate (after Rouainia et al. 2015).

In addition to permeability and vegetation, the sensitivity of the model outputs to pre-failure stiffness was investigated. In the modelling undertaken in this work, the Young's modulus (E) of the material was made dependent on the mean effective stress (p'), based on a stiffness multiplier (E_0) as per the work of Potts et al. (1997), see equation (1).

$$E = E_0 \frac{(p' + 100)}{100} \tag{1}$$

The adopted value of this multiplier and hence the pre-failure stiffness was shown to have a significant impact on progressive failure and slope stability. This is due to the fact that increased stiffness leads to an increase in the rate that shear strength is mobilised within the soil mass before significant strain-softening is able to occur in areas where yielding is observed. As such the higher stiffness values should lead to more rapid mobilisation of strength and so cause a reduced rate of progressive failure. The above mechanism was originally described in work undertaken by Ellis and O'Brien (2007), see Figure 14.

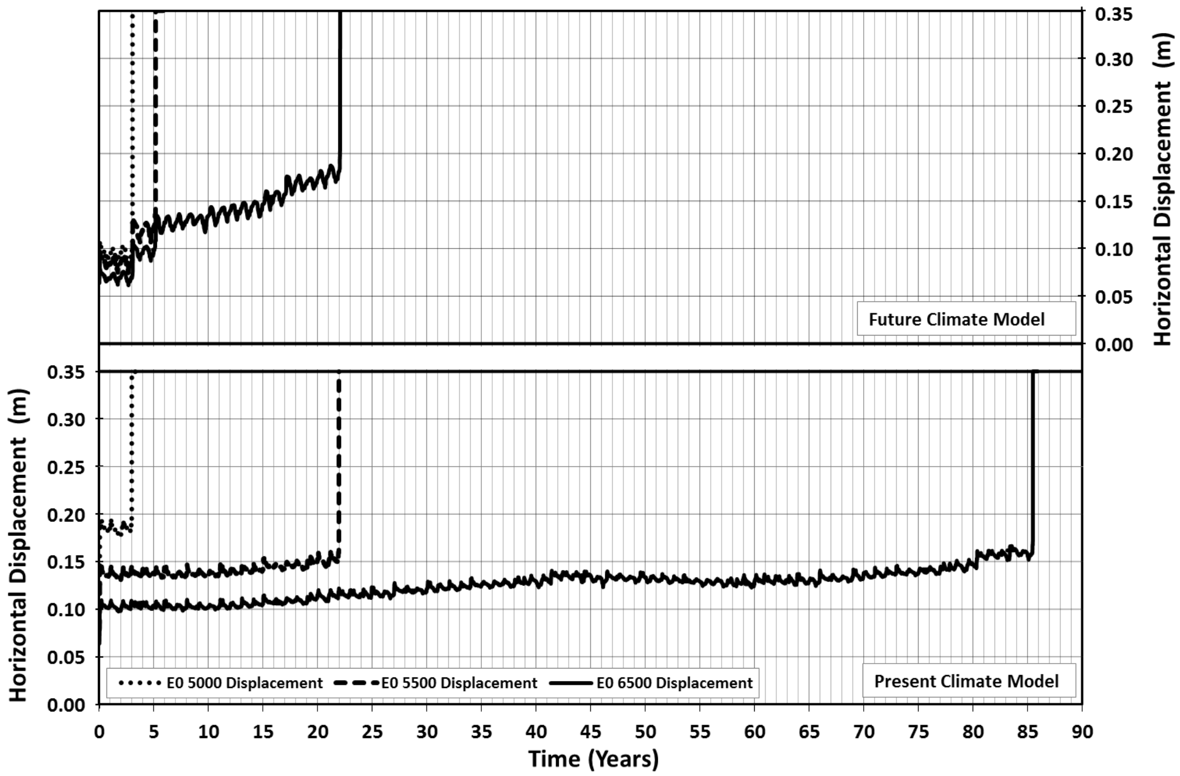

Figure 14. Effect of pre-failure stiffness on cut-slope stability due to imposed present and future climates.

The results of the modelling this far have provided useful insights into the sensitivity of the model outputs to a number of parameters. This has been useful to inform the future field and laboratory testing programmes. Furthermore, it has provided confidence that the models can capture some of the observed behavior in the field and provided an indication that both changes in climate and weather event sequences will change the current performance of engineered slopes. This will necessarily require a change in the way in which these slopes must be managed in the future.

The aim for future work is to use the validated models to investigate systematically how differing soil types, slope geometries and types of vegetation cover effect slope hydrology and related deformations under differing climate and weather scenarios.

The aim will be to identify the relative hazard posed to differing infrastructure slopes by climate change and also to identify patterns of weather which lead to or increase slope instability to allow broad lessons to be learned which can be applied across a range of infrastructure scales from individual slopes to a network scale.

6. Towards network-scale

As discussed in Section 1, iSMART operates across three scales; the soil-water-vegetation system of a single slope (scale 1) and the systems of slopes (scale 2) that make up a transport network (scale 3). The project is now developing methods to integrate the results from scales 1 and 2 into a whole-network model to advance systems-scale understanding of future network responses and vulnerabilities. To date, much of iSMART's activities have focused on achieving a better understanding of what parameters are representative of asset conditions and what process models describe best what is observed at the field sites. In the first phase of the research, rigorous numerical modelling at the site level has been used to bring together field and laboratory-scale data and to examine the consequences for slope performance, responding to actual and forecasted weather event sequences. This process has informed the direction of the laboratory and field work to quantify unknown parameters and understand complex processes. The translation of this information into appropriate serviceability and ultimate limit state of the assets is now being developed in discussion with the stakeholders and this will inform the condition appraisal of systems of slopes. Once this is better understood, it will enable the assessment of the spatial and temporal variability of the condition of engineered earthworks for UK transport networks. In turn, as discussed in Section 1, this knowledge will provide network operators with advice on asset design, management, maintenance and investment strategies (Figure 15).

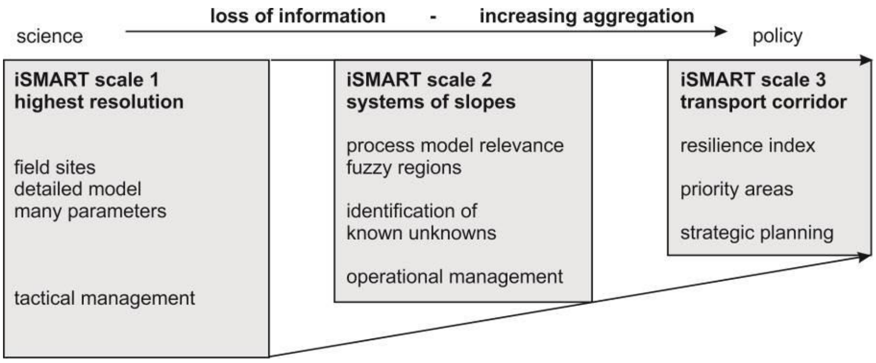

Figure 15. Integration across scales – the iSMART approach (adapted from Dijkstra et al. 2015).

As the pathway of upscaling the iSMART research is based on rigorously tested physical process models, it will be feasible to incorporate (and evaluate the outcomes of) changes in climate and environmental conditions. This is a significant advantage over current industry approaches that have assessed the vulnerability of transport infrastructure slopes on the basis of largely empirical information or expert elicitation (e.g. URS 2010). These models are very important as these use the currently available dataset and knowledge to enable some degree of prioritisation of earthworks asset conditions (slotting into scale 2 of the diagrams depicted in Figures 2 and 15). However, these result in relatively static products where it is difficult to evaluate the changes in conditions over time as climate/environmental change progresses (see Dijkstra and Dixon 2010). iSMART therefore focuses on continuity in the analysis, allowing detailed process models (scale 1) to inform slope system condition assessments (scale 2) and this, in turn to inform transport network performance (scale 3).

There is an increasingly fuzzy spatial relevance associated with the upscaling process. At the highest resolution, it is envisaged that data are available that are highly site specific, feeding into detailed process models. iSMART is delivering critical monitoring/observational datasets against which process models can be tested. However, distillation of site data and process understanding leads to the identification of common parameters and processes that represent systems of slopes of a similar nature (embankment/cutting/age/geology). These have a much larger spatial relevance, but this relevance will fade the further removed the asset conditions are from our field sites. It is important to note that this is not strictly a spatial distance, but a distance expressed as a parameter/process similarity function and this thus leads to complex patterns of relevance along the network (Figure 16). The current research does not claim to offer all answers to the known unknowns, but this exercise will highlight the relevance of the project to the transport network as a whole and indicate where further work on the characterisation of parameters and process is still required. An important step forward is the improved understanding of critical combinations of geology, asset condition, geometry and vegetation impacts.

Further integration of the understanding of the depths of pore water pressure cycling (gained from field monitoring) will enable the understanding of soil deterioration processes (from laboratory testing) be built into the numerical models, which will incorporate future climate scenarios. Hence, asset deterioration will be modelled to enable better estimations of current asset condition based on age, and projection of asset behaviour under future weather and environmental conditions.

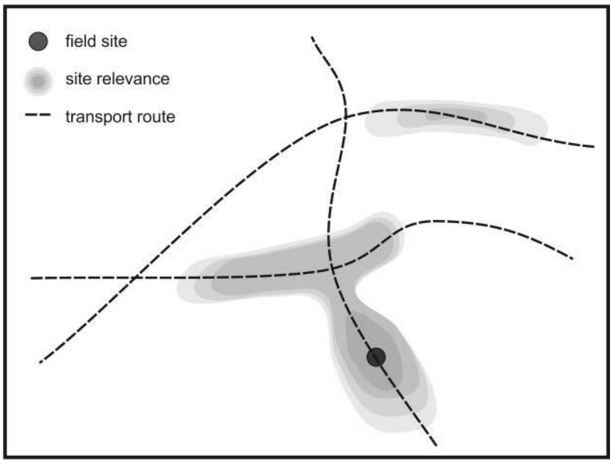

Figure 16. Conceptual diagram of the upscaling process. Field sites will deliver property/parameter information and process relevance that extends beyond the boundary of these sites. However, the relevance of this information will fade with ‘distance’ (indicated by the increasingly lighter shades of grey).

Validated models that incorporate the greater complexity outlined above will form the basis of the production of a national scale map of the forecasted capacity reduction of transport networks due to slope instability caused by climate effects at several future time slices. In turn, the models will enable testing of the benefits of different stability and maintenance solutions under a changing climate regime and thus enable development of robust adaptation strategies in conjunction with a formal stakeholder dialogue. The long-term vision of the project is to enable a 4D model of transient water movement in infrastructure slopes under a range of current and future environmental scenarios based on a fundamental understanding of earthwork material and system behaviour, which can be used to create a more reliable, cost effective, safer and more sustainable transport system.

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